# THE EFFICACY OF PASSIVE LIMITER PUMPING OF NEUTRAL PARTICLES

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## Abstract

Large neutral gas accumulation has been observed in trapped volumes directly behind the mechanical limiter in the Alcator A tokamak. Experiments have been performed to measure the neutral pressure buildup behind the limiter as a function of plasma density and gas species. The results indicate that a passive mechanical limiter effectively removes from the vacuum vessel up to 20% of the atoms injected during a discharge. The feasibility of mechanical limiters removing the fusion reaction helium ash, thus negating a major need for magnetic divertors, is discussed.


## I. Introduction

As present day tokamaks continue to make significant advances in the achievement of high plasma temperatures and high $n\tau_E$ values, more effort is being directed towards the control of impurities and the helium ash which is a product of the D-T fusion reaction. Future tokamaks are being planned which will utilize the principal of magnetic divertors to achieve the desired impurity and helium control. Although the divertor concept is feasible, the requisite additional magnetic coils significantly complicate the engineering and maintenance aspects of a large tokamak reactor.

Strides have already been made in the operation and preparation of currently operating tokamaks via the use of Taylor discharge cleaning, glow discharge cleaning, gettering, etc., and meticulous vacuum techniques such that plasma $Z_{eff}$'s $\lesssim$ 1.5 and low heavy metal radiation have been routinely achieved in various tokamaks.[1-9] It appears possible to readily extrapolate these methods to future devices, and conceivably tokamak reactors, to the extent that divertors may not be necessary for low Z and heavy metal impurity control. Helium ash, however, may not be adequately removed or controlled by any of the above currently employed techniques. To sustain a controlled, steady-state D-T burn, one must be capable of maintaining a fixed alpha particle density. This may be accomplished by decreasing the alpha particle recycling to balance the fusion alpha production rate. For typical ignition size plasmas and plasma parameters, the steady state conditions may be achieved if approximately 10% or more of the alpha particles are not recycled; in other words, if they are pumped away.[10,11,12] One possible way to do this is by using a passive mechanical limiter, comparable to those promoted by Schivell[13] and later expanded upon by others.[10]

In this paper we report the experimental results of the effectiveness of a passive limiter pumping scheme. In section two the limiter and vacuum geometry are discussed. Section three, four, and five present the experimental observations, the discussion, and the conclusion, respectively.

## II. Limiter and vacuum geometry

The experiments were performed on the Alcator A tokamak, which has been described extensively in the literature.[1,7] Figure 1a schematically illustrates the vacuum vessel, which is made of stainless steel bellows welded to four equally spaced, stainless steel diagnostic port flanges. The vessel has a major radius of 54 cm and a minor radius of 12.5 cm. The total volume of the torus and the diagnostic port extension tubes is 451 liters; the vacuum is maintained with two 500 ℓ/s turbo-molecular pumps as shown.

A single molybdenum limiter is inserted from the horizontal port as shown in Figures 1a, b. The limiter is electrically floating and isolated from the vacuum vessel, which is grounded at one of the pumping stations. The toroidal thickness of the limiter is 1.1 cm with a poloidal extension of 205°. The limiter inner radius (plasma radius) is 10.4 cm and the outer radius is 12.2 cm.

At the limiter flange there are three port extension tubes. The top (volume 3) and the bottom (volume 1) have volumes of 13.3 and 13.7 liters respectively. Each is connected to the main toroidal vacuum vessel via two rectangular slots (approximately 5.9 cm x 1.3 cm x 20 cm long) as shown in Figure 1b. The horizontal port (volume 2) is much smaller, with a volume of 2.1 liters, connected to the vacuum vessel by a rectangular slot of dimensions 1.6 cm x 17 cm x 16.7 cm long. At the end of each of the volumes a fast response, absolute pressure gauge is mounted to measure the pressure increase in the three respective limiter port volumes. Each of the pressure gauges has a response time of $\lesssim$ 5 ms with a pressure range of $10^{-5}$ to 1 torr and absolute error of $\lesssim 5.0 \times 10^{-5}$ torr. It should be noted that none of the three volumes has any external pumps or gas sources associated with them.

During plasma operation the plasma density is increased by the injection of neutral gas through a fast piezo-electric valve from the top port located 180° toroidally from the limiter. The exact number of molecules (atoms) injected into the torus during the discharge is known by measuring the pressure drop in a 70 $cm^3$ plenum directly behind the fast valve. At the same toroidal location a stainless steel ICRF antenna is inserted from the horizontal. The antennae has a 120° poloidal extension, 60° above and below the toroidal midplane, with an inner radius of 10.7 cm and the back surface flush (and in electrical contact) with the vacuum vessel wall.

## III. Experimental Observations

Neutral gas pressure measurements in the limiter port volumes were made during routine ohmically heated plasma operation. Typical plasma parameters were $B_T$ = 60 kG, peak plasma currents $130 \lesssim I_p \lesssim 200$ kA, with the plasma density and working gas as variables. Profiles and central values of $n_e$, $T_e$, and $T_i$ are comparable to those reported elsewhere[7] for similar operating conditions.

The discharge is initiated by applying a large voltage to the low pressure, steady state fill gas (typically 4-8 x $10^{-5}$ torr.) The number of atoms in the vacuum vessel during plasma initiation is 2-3 orders of magnitude below the number of atoms injected during the discharge to increase plasma density. Discharge duration is typically between 115 and 140 ms, with the slightly longer discharges occuring at the lower plasma densities.

Figure 2 shows a typical $D_2$ discharge evolution for peak line-average density of $\bar{n}_e = 4.3 \times 10^{14} cm^{-3}$. The time scale is 20 ms per division. The top four traces are the loop voltage, plasma current, plasma density, and neutral gas injection pressure waveform respectively. During the constant pressure portion of the gas injection the plasma density increases approximately linearly in time, peaking about 10 ms after the valve turns off and gas in the injection volume continues to empty into the torus. The bottom three traces are the outputs for the three pressure gauges, 3,2,1 respectively. There is no pressure rise in the top port, V.3, until well after the discharge has terminated. This is presumeably due to the desorption of some of the working gas from the cold walls. It should also be noted that no portion of the limiter is directly in front of the access slots to V.3. The pressure trace from V.2, the side port, shows a small linear increase with density for $\bar{n}_e \lesssim 2 \times 10^{14} cm^{-3}$. For higher density the pressure increases more rapidly, with a temporal behavior similar to the remaining density rise but with a 10-15 ms time lag, which is the approximate response time of the port. Volume 1 shows a much larger pressure increase, peaking at ≈ 27 microns at about 180 ms. This much slower time response is reasonable considering the significantly larger volume of V.1 (13.7 ℓ) and an associated slower response time of ≃ 100 ms due to the smaller and longer slots connecting the volume to the toroidal vacuum vessel.

Figure 3 shows the peak neutral pressure measured in volume 1 (limiter bottom port) as a function of line average density for the 3 working gases of $H_2$, $D_2$, and He. A clear trend is evident for all three gases, although a large number of He data points have not yet been obtained. The neutral gas accummulation is small, increasing slowly with density for $\bar{n}_e \lesssim 2 \times 10^{14} cm^{-3}$. For higher plasma density the slope of the port pressure versus the plasma density increases by a factor of 5 to 6, with port pressures as high as 29 microns having been measured in $D_2$ at $\bar{n}_e \simeq 5.1 \times 10^{14} cm^{-3}$. It is worthwhile to note that these pressures are one to two orders of magnitude higher than the steady state fill gas pressure and are factors of 5 to 10 higher than the pressure rise measured from pulsing cold gas into the torus with no plasma. In addition, we have made pressure measurements at other no-limiter ports. The behavior has been similar to that measured in volume 3 above the limiter. In all cases we have found no pressure increases in non-limiter ports until well after discharge termination, i.e. 200 to 300 ms later, and the pressure rises have been on the order only 2 to 3 microns for the highest density discharges. As stated previously, this is presumeably due to the gradual desorption of some of the working gas that has been retained by the chamber wall during the plasma discharge.

## IV. Discussion

The observation of large neutral pressure buildup in trapped volumes directly behind the mechanical limiter is not in itself surprising. If one has a relatively tenuous plasma in the limiter shadow, there may be large fluxes of charged particles to the limiter where they become neutralized and scatter ballistically and/or recycle from the limiter to form a dense neutral cloud in the immediate vicinity of the limiter.

Measurements of the shadow plasma properties in JFT-2 indicate that as much as 80% of the charged particle flux is to the limiter versus the wall.[14] Similar measurements of the shadow plasma in Alcator A[15] indicate that typically greater than 90% of the flux is incident on the limiter. In view of the high magnetic field most of the ion flux would be normal to the limiter face. For grounded limiters the parallel flux would be

$$\Gamma_{\parallel} = n_i \, \bar{v}_{\parallel i}$$

where $\bar{v}_{\parallel i}$ is the parallel ion thermal velocity. Floating limiters, such as ours, should have a sheath potential, thereby accelerating the ions into the limiter, thus

$$\Gamma_{\parallel} = n_i \, \overline{V}_{si}$$

where $\overline{V}_{si} \simeq [(T_i + 3\ T_e)/m_i]^{1/2}$ is the ion sound speed. For incident ion energies of less than several hundred eV, experimental data and computer calculations indicate that more than 50% of the incident ions are reflected.[16] Of those reflected 80-85% come off as neutrals with an energy distribution peaked at the energy of the incident ions (for energies $\lesssim$ 2 keV) and a cosine angular distribution.[16,17] With the limiter thus acting as a large neutral source, one might expect enhanced $H_\alpha$ emission and recycling within several mean free paths for ionization toroidally from the limiter, as has been observed in both TM-3[18] and Alcator A.[19]

As has already been shown, the number of neutrals that are effusively or are ballistically scattered off the limiter into the limiter ports is large. One can get a better feeling for the scale of this by plotting the total fraction of injected atoms collected in the limiter bottom and side ports (volumes 1 and 2 respectively), as done in Figure 4. These data were taken from $D_2$ discharges for $B_T$ = 60 kG and 140 $\lesssim I_p \lesssim$ 200 kA. The differences between the solid points and the circles reflect the effects of recycling of neutral gas from the wall to maintain plasma density. Circles represent discharges for which the number of injected atoms was increased from the previous discharge such that the peak plasma density was higher than the preceding discharges; the solid points are for discharges for which the number of injected atoms was decreased from the previous shot such that the peak density was lower than the preceding shot. We observe that for lower densities, e.g. $\bar{n}_e \lesssim 1 \times 10^{14} cm^{-3}$, only 3-4% of the injected particles are "pumped into the limiter ports. However, for line average plasma densities above $2 \times 10^{14} cm^{-3}$ the fraction of "pumped" particles increases with density, attaining a level of 20% for $\bar{n}_e \approx 5 \times 10^{14} cm^{-3}$ in deuterium.

The surface area of the limiter bottom and side apertures is only $1.5 \times 10^{-3}$ of the total surface area of the toroidal vacuum vessel wall. Comparing this number to the fraction of injected atoms actually deposited into the limiter ports we find that the presence of the limiter has provided a "pumping" enhancement of 20 to 200 for the density ranges investigated.

Another way to quantify the "pumping" efficiency is to compare the measured flux of particles entering the limiter side and bottom trapped volumes to the average flux of particles leaving the plasma volume, as deduced from the global particle confinement time.[19] Over the density range investigated with $D_2$, 1.5% to 10.5% of the particle flux from the plasma edge enters the limiter port aperatures. This also indicates a factor of 10 to 100 "pumping" enhancement over the strict surface area ratio of the limiter port aperatures to the vacuum vessel wall.

Since the data are limited for He discharges, one cannot make a precise quantitative statement as to the relative pumping efficiency between H or D and He. However, Figure 3 plots the bottom limiter port pressure increase versus $\bar{n}_e$. Were we to plot port pressure versus $\bar{n}_i$ then we would find that the He is pumped at least as well if not better than H or D for the same line average ion density since a helium discharge would have $2\bar{n}_i = \bar{n}_e$.

## V. Conclusion

Ultimately the goal of a passive limiter pumping scheme is to remove ∿ 10% of the fusion produced helium from the plasma edge to allow a sustained D-T burn in a reactor. If the helium concentration is uniform throughout the main plasma and limiter shadow, then our results would imply that from 4-20% of the helium, as well as the fuel gas, could be adequately removed by a mechanical limiter pumping scheme. Any dependence on the spatial distribution of the He would also be a limitation of a magnetic divertor as well. However, there is reason to believe that the limiter pumping scheme would actually enhance the relative fraction of helium removed. The charge exchange cross section for helium is approximately a factor of 10 to 20 lower than that for D and T at the temperatures expected at the edge of reactor grade plasmas.[20,21,22] There should be very little charge exchange of the alphas on the refuelling gas or pellet. Thus, most of the He will leave the bulk plasma and enter the limiter shadow as charged particles. There the He ions will diffuse to the limiter and become neutralized. Depending on the design of the limiter and the associated pumping port access to the limiter, a significant portion of the neutralized He would be removed.

Finally, we feel that the results presented here warrant new and additional consideration of the use of mechanical limiters instead of divertors in the next generation of tokamaks.

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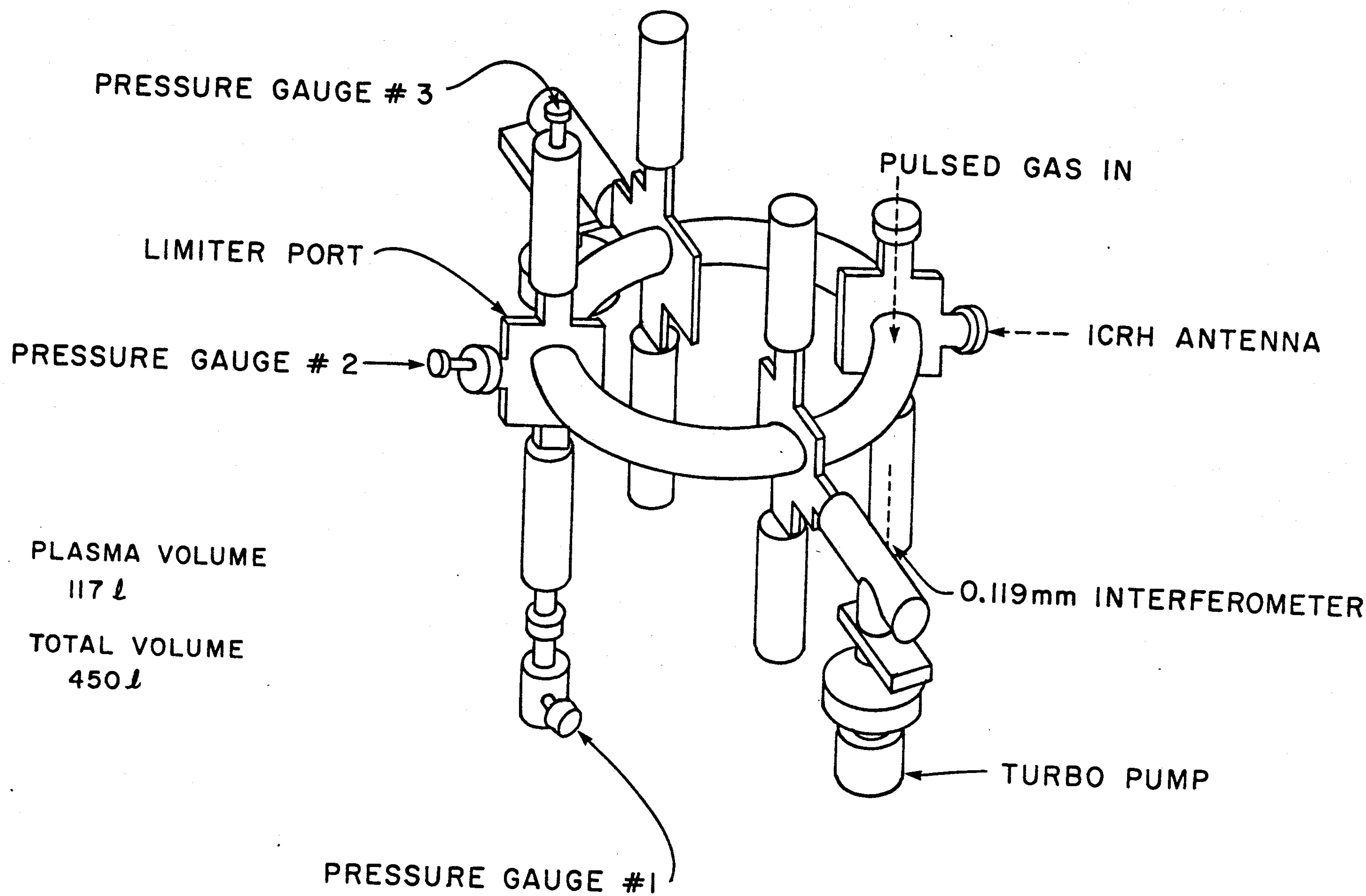
## Figure Captions

Figure 1 a) A schematic of the Alcator A vacuum vessel;
b) Cutaway view in the poloidal plane of the Mo limiter and the port slots,

Figure 2 Temporal evolution of a typical deuterium discharge for $B_T = 60$ kG. The bottom three traces are the signal outputs from the pressure gauges in the limiter volume top, side, and bottom respectively. The fast neutral gas valve is opened $\approx$ 5 ms before discharge initiation.

Figure 3 Maximum gas pressure measured in the limiter bottom port as a function of peak line average density and various gases. All measurements for $B_T = 60$ kG, $130 \leq I_p \leq 200$ kA.

Figure 4. The percentage of the injected atoms collected in the limiter side and bottom ports as a function of peak line average density. $B_T = 60$ kG, $140 \leq I_p \leq 200$ kA, deuterium.



PRESSURE GAUGE # 3
PULSED GAS IN
LIMITER PORT
PRESSURE GAUGE # 2
ICRH ANTENNA
PLASMA VOLUME
117 ℓ
TOTAL VOLUME
450 ℓ
0.119mm INTERFEROMETER
TURBO PUMP
PRESSURE GAUGE #1


FIGURE 1 A

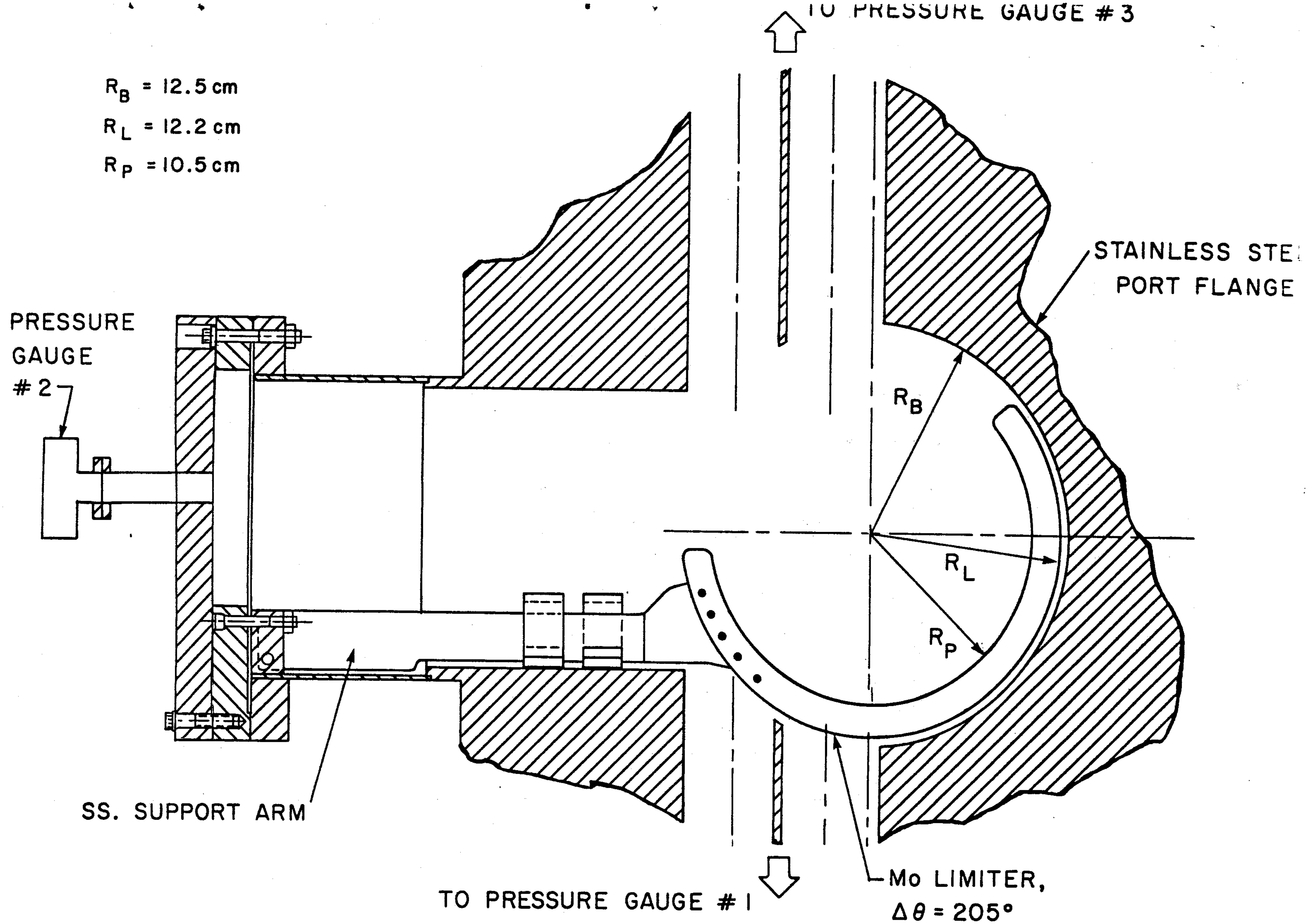
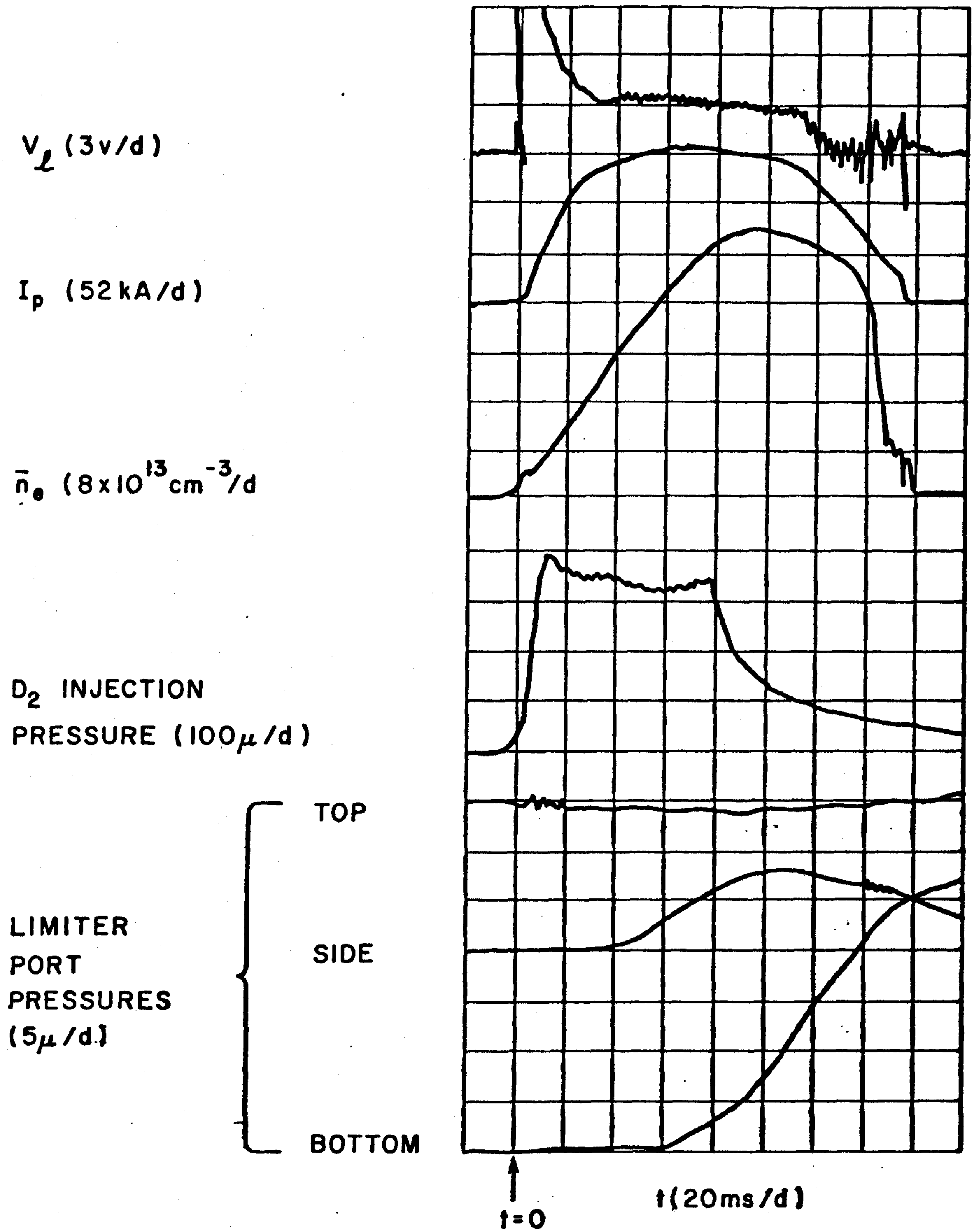

TO PRESSURE GAUGE # 3
$R_B$ = 12.5 cm
$R_L$ = 12.2 cm
$R_P$ = 10.5 cm
STAINLESS STE
PORT FLANGE
PRESSURE
GAUGE
# 2
$R_B$
$R_L$
$R_P$
SS. SUPPORT ARM
TO PRESSURE GAUGE # 1
Mo LIMITER,
$\Delta\theta$ = 205°

FIGURE 1 B



$V_\ell$ (3v/d)
$I_p$ (52kA/d)
$\bar{n}_e$ ($8\times10^{13}$ cm$^{-3}$/d
$D_2$ INJECTION
PRESSURE ($100\mu$/d)
TOP
LIMITER
PORT
PRESSURES
($5\mu$/d)
SIDE
BOTTOM
t=0
t(20ms/d)


FIGURE 2

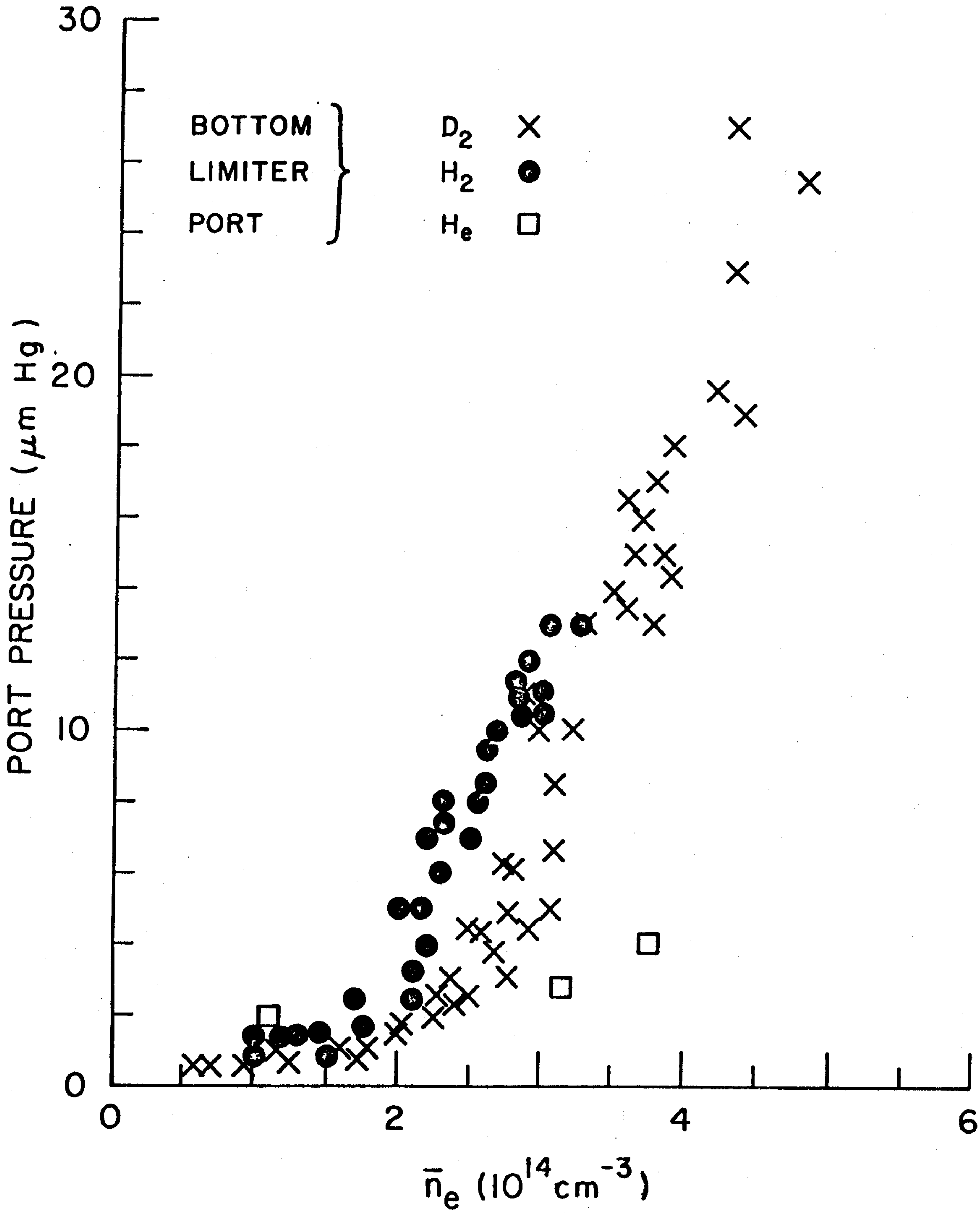

30
20
10
0
0
2
4
6
PORT PRESSURE (μm Hg)
$\bar{n}_e$ ($10^{14}$ cm$^{-3}$)
BOTTOM
LIMITER
PORT
$D_2$
$H_2$
$H_e$

FIGURE 3

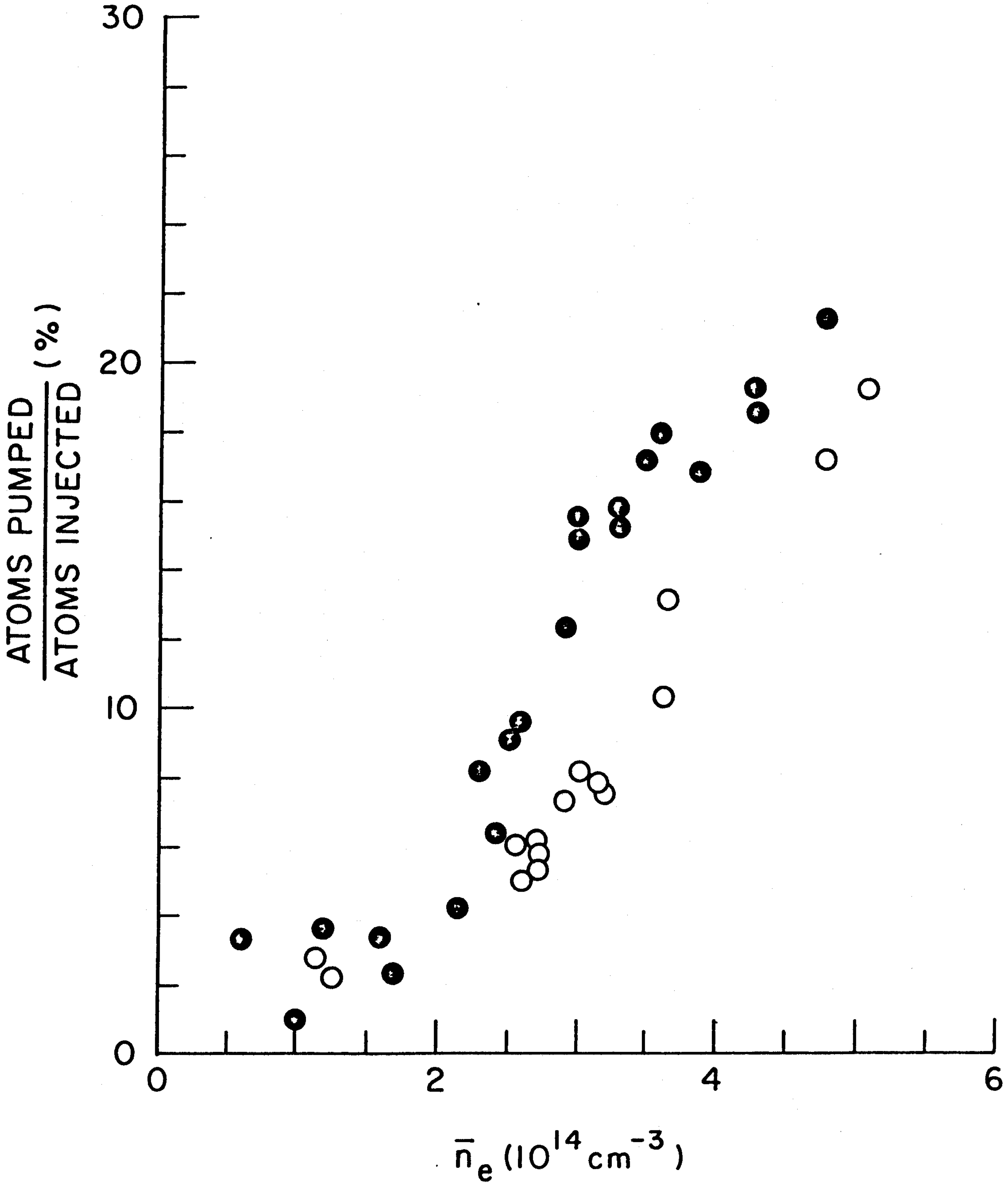



FIGURE 4